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AN EXPERIMENTAL STUDY ON SURFACE ROUGHNESS - APPLIED TO DETERMINE THE OPTIMAL VALUE OF CUTTING PARAMETERS WHEN MILLING 40Cr STEEL

Dr. NGUYEN HONG SON[1] & Dr. DO DUC TRUNG[2]

[1]*Lecturer, Center for Mechanical Engineering, Hanoi University of Industry, Hanoi, Vietnam*

[2]*Faculty of Mechanical Engineering, Hanoi University of Industry, Hanoi, Vietnam*

ABSTRACT

This paper presents an experimental study on surface roughness parameters. On that basis, a more comprehensive view of surface roughness was given. Experiments on milling 40Cr steel with a face mill have been carried out to build the relationship between surface roughness and cutting parameters. A multi-objective optimization problem was also performed to determine the value of the cutting parameters to ensure that the machined surface has a small value of roughness.

KEYWORDS: Surface Roughness, The Arithmetic Average Height Parameter, Maximum Height of Profile, Ten Point Height, 40Cr Steel & Milling - Cutting Parameter

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Original Article

1. INTRODUCTION

The milling method is a method, commonly used in machine manufacturing and is known to be one of the most productive machining methods. When studying the milling process, besides studying to improve productivity, studies on surface quality when milling are also interested by many scientists. In particular, surface roughness is one of the most frequently considered parameters when studying surface quality.

Each part, working under different conditions will have different roughness requirements. Surface roughness does not only need to be evaluated through the height of the microscopic surface roughness, or the depth of the valleys, or the distance between the roughness peaks, etc. but based on the working requirements of the parts in specific conditions, surface roughness will need to be considered with different perspectives (parameters) [1], [2].

To have an insight about surface roughness, it is necessary to study on surface roughness with many different criteria. According to ISO 4287-1997 [3], for a comprehensive evaluation of surface roughness, up to 14 parameters which are summarized in Table 1 need to be measured.

Table 1: Parameters Defined in IS0 4287-1997

No.	Symbol	Defined
1	R_p	Maximum profile peak height
2	R_v	Maximum profile valley depth
3	R_a	Arithmetical mean deviation of the assessed profile
4	R_c	Mean height of profile elements
5	R_t	Total hight of profile
6	R_z	Maximum height of profile
7	R_q	Root mean square deviation of the assessed profile
8	R_{sk}	Skewness of the assessed profile
9	R_{ku}	Kurtosis of the assessed profile

10	R_{Sm}	Mean width of the profile element
11	R_{dq}	Root mean square slope of the assessed profile
12	$R_{mr(c)}$	Material ratio of the profile
13	R_{dc}	Profile section height differences
14	R_{mr}	Relative material ratio

However, the number of surface roughness parameters that can be measured depends on the ability of each type of measuring equipment (surface roughness tester). Therefore, to simplify the evaluation of surface roughness, ISO 4288-1996 [4] provides two parameters commonly used to evaluate surface roughness as in Table 2.

Table 2: Parameters Defined in IS0 4288-1996

No.	Symbol	Defined	Measurement range
1	R_a	Arithmetical mean deviation of the assessed profile	0.006 µm < $R_a \leq$ 80 pm
2	R_z	Maximum height of profile	0.025 µm < $R_z \leq$ 200 prn

Gadelmawla et al. [1] have explained these two parameters as follows:

The arithmetic average height parameter (Ra), also known as the centre average (CLA), is the most universally used roughness parameter for general quality control. It is defined as, the average absolute deviation of the roughness irregularities from the mean line over one sampling length as shown in Figure 1. This parameter is easy to define, easy to measure, and gives a good general description of height variation. It does not give any information about the wavelength and it is not sensitive to small changes in profile. The mathematical definition and the digital implementation of the arithmetic average height parameter are, respectively, as follows:

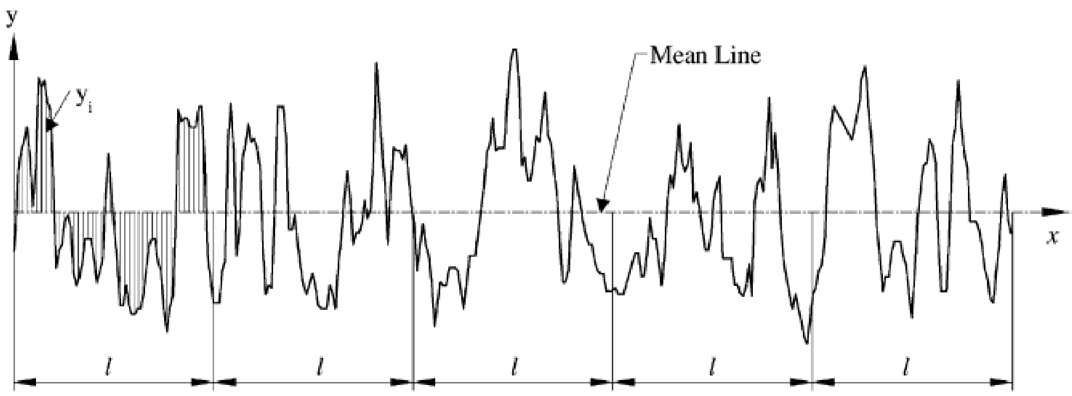

Figure 1: Definition of the Arithmetic Average Height (Ra).

$$R_q = \frac{1}{l}\int_0^l |y(x)|dx \tag{1}$$

$$R_a = \frac{1}{n}\sum_{i=1}^{n}|y_i| \tag{2}$$

Maximum height of profile (ten point height - Rz) is more sensitive to occasional high peaks or deep valleys than Ra. It is defined by two methods, according to the definition system. The international ISO system defines this parameter as the difference in height between the average of the five highest peaks and the five lowest valleys along the assessment length of the profile. The Germany DIN system defines Rz, as the average of the summation of the five highest peaks and the five lowest valleys along assessment length of the profile. Figure 2 shows the definition of the ten – point height parameter. The mathematical definitions of the two types of Rz as follows:

$$R_{z(ISO)} = \frac{1}{n}\left(\sum_{i=1}^{n} p_i - \sum_{i=1}^{n} v_i\right) \tag{3}$$

$$R_{z(DIN)} = \frac{1}{2n}\left(\sum_{i-1}^{n} p_i + \sum_{i-1}^{n} v_i\right) \tag{4}$$

Where, n is the number of samples along the evaluation length.

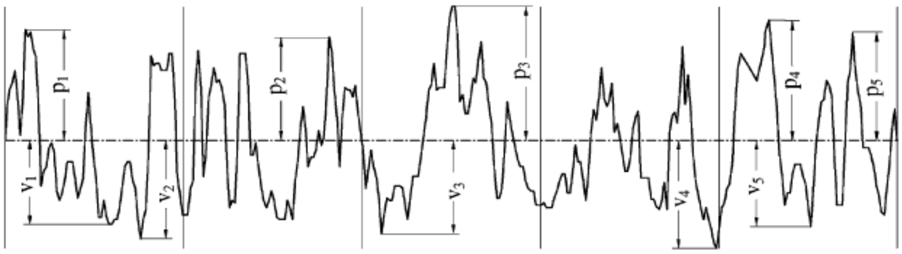

Figure 2: Definition of Ten-Point Height Parameter (Rz(ISO); Rz(DIN)).

The definitions of Ra and Rz above show that there is almost no relationship between these two parameters. A surface with small Rz value does not mean small Ra value, and vice versa. The example illustrated in Figure 3 will show that the two surfaces with the same Rz may have greatly different Ra values.

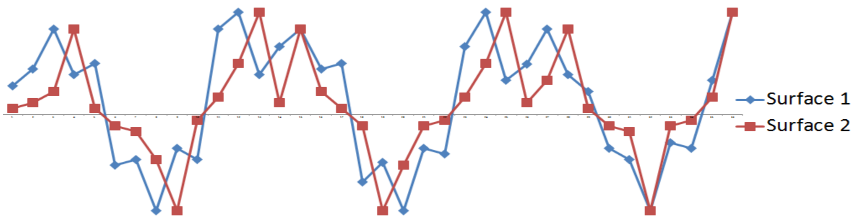

Figure 3: The Two Surfaces have the Same R_z Value.

Therefore, to assess the surface roughness more fully, both Ra and Rz parameters need to be investigated. However, in each study carried out, the authors usually considered either Ra or Rz, not many studies mentioned both Ra and Rz within a study. In addition, there have been some studies showing that machining conditions that make the value of Ra small but Rz has great value, and vice versa. For example, BN Pathak et al. [5] when investigated the effects of cutting parameters on surface roughness when milling two types of Al-1Fe-1V-1Si and Al-2Fe-1V-1Si materials have obtained some results as shown in Figure 4 to Figure 6.

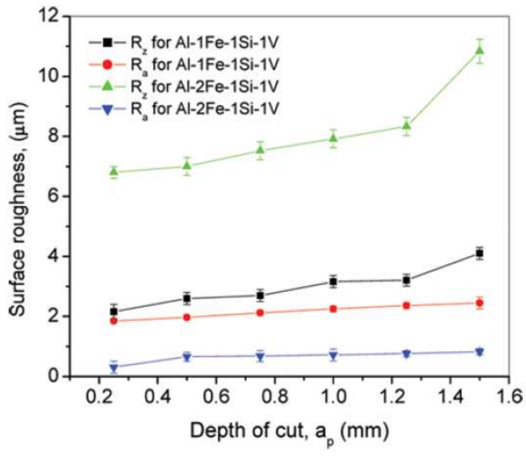

Figure 4: Effects of the Depth of Cut on Surface Roughness [5].

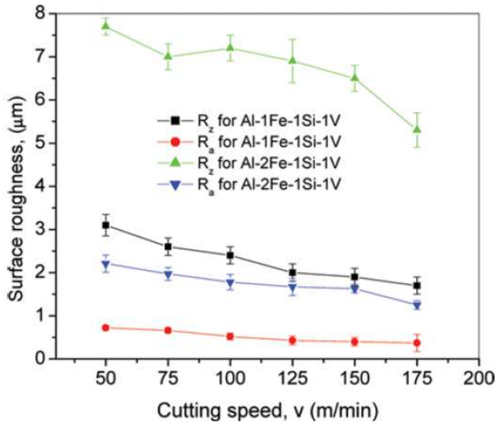

Figure 5: Effects of Cutting Speed on Surface Roughness [5].

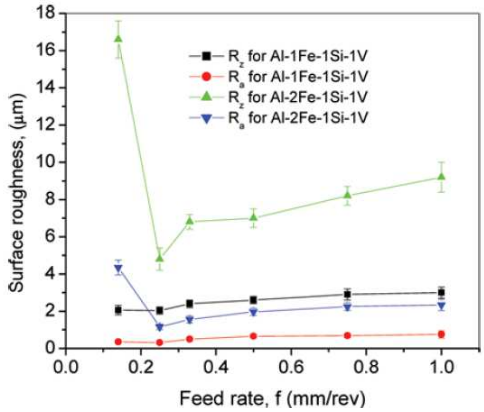

Figure 6: Effects of Feed Rate on Surface Roughness [5].

The result in Figure 4 shows that:

- When increasing the value of depth of cut, the Ra value is almost unchanged, while the Rz value increases rapidly in the case of milling Al-2Fe-1V-1Si.
- Ra value when milling Al-1Fe-1V-1Si is larger than Ra when milling Al-2Fe-1V-1Si, but the Rz value when milling Al-2Fe-1V-1Si is much larger than the value of Rz when milling Al-1Fe-1V-1Si;

The result in Figure 5 shows that:

- When increasing cutting speed, Ra, Rz values of Al-1Fe-1V-1Si and Ra values of Al-2Fe-1V-1Si tend to decrease slowly, while Rz values of Al-2Fe- 1V-1Si decreases very fast.
- The Ra value of Al-1Fe-1V-1Si and that of Al-2Fe-1V-1Si are not much different, while the Rz value of Al-2Fe-1V-1Si is much larger than the Rz value of Al -1Fe-1V-1Si.

Figure 6 shows that:

- When the feed rate increases from 0.1 to 0.2 (mm/rev): the Ra, Rz values of Al-1Fe-1V-1Si and the Ra value of Al-2Fe-1V-1Si change insignificantly, while the Rz value of Al-2Fe-1V-1Si decreases very fast.
- When the feed rate increases from 0.2 to 1.0 (mm/rev): the Ra, Rz values of Al-1Fe-1V-1Si and the Ra value of Al-2Fe-1V-1Si change insignificantly, while the Rz value of Al-2Fe-1V-1Si increases very fast.

- The Ra value of Al-1Fe-1V-1Si and that of Al-2Fe-1V-1Si are not much different, while the Rz value of Al-2Fe-1V-1Si is much larger than the Rz value of Al -1Fe-1V-1Si.
- The feed rate has a great effect on Rz when milling Al-2Fe-1V-1Si, but has a very small effect on Ra.

Some of the above analysis shows that in order to evaluate the surface roughness of the workpieces in full, it is necessary to have studies on both Ra and Rz parameters in each specific condition. In this paper, we will determine the optimal value of cutting parameters when milling 40Cr steel, to ensure that both Ra and Rz have the smallest values.

2. MILLING EXPERIMENT

The experimented material is 40Cr steel, which is common steel in the machine manufacturing with good machinability, often used to make parts under static load, sometimes also used to produce impact-resistant parts during work, parts with abrasion-resistant surfaces such as types of shaft and gear.

The experiments are conducted on DOOSAN DNM 400 milling machine. The face mill tool with four PVD-coated inserts is used in this study.

Ra and Rz are measured using SJ201 surface roughness tester (Mitutoyo - Japan). Each component must be measured at least 3 times. The Ra and Rz values at each experiment are the average of successive measurements.

The experimental plan is carried out, when changing the value of cutting parameters including cutting speed, feed rate and depth of cut as shown in Table 3. Ra and Rz values, when measuring for each component are also summarized in table 3.

Table 3: Experimental Plan and Results

No.	v, (m/min)	f,(mm/z)	t, (mm)	R_a, (µm)	R_z, (µm)
1	185	0.18	0.4	1.48	6.83
2	185	0.13	0.2	0.99	2.98
3	223.65	0.16	0.281	0.86	4.34
4	185	0.13	0.4	0.29	1.69
5	185	0.13	0.4	0.26	1.30
6	223.65	0.16	0.519	0.15	0.88
7	250	0.13	0.4	0.26	1.71
8	185	0.08	0.4	0.18	1.49
9	185	0.13	0.4	0.41	2.19
10	185	0.13	0.6	0.13	0.77
11	185	0.13	0.4	0.37	1.55
12	185	0.13	0.4	0.57	2.09
13	146.35	0.16	0.281	0.78	4.16
14	146.35	0.10	0.281	0.26	1.45
15	223.65	0.10	0.281	0.47	2.35
16	185	0.13	0.4	0.34	1.69
17	120	0.13	0.4	0.16	0.98
18	146.35	0.10	0.519	0.65	3.51
19	223.65	0.10	0.519	0.40	2.44
20	146.35	0.16	0.519	0.27	1.75

3. SINGLE-OBJECTIVE OPTIMIZATION

Used Minitab 16 statistical software, to analyze the data in Table 3. After eliminating the quantities with very small coefficients (based on the P-value probability value), the relationship between Ra, Rz values and the cutting parameters are

indicated by the following two equations. These two equations are the basis for determining the value of the cutting parameters depending on the specific requirements of Ra and Rz values.

$$R_a = -2.227 + 0.025 * v - 15.756 * f + 5.939 * t + 166.657 * f^2 \\ +3.682 * t^2 - 0.018 * v * t - 53.922 * f * t \qquad (5)$$

$$R_z = -7.347 + 0.042 * v - 108.254 * f + 43.555 * t + 985.494 * f^2 \\ +4.447 * t^2 - 0.056 * v * t - 0.082 * v * f - 280.812 * f * t \qquad (6)$$

From the equations (5) and (6), solved the problem of optimizing each objective (Ra and Rz) to determine the set of values of parameters for machining the workpieces surface with the small Ra, or the smallest Rz. The optimal graph for these two criteria is shown in Figures 7 and 8, respectively.

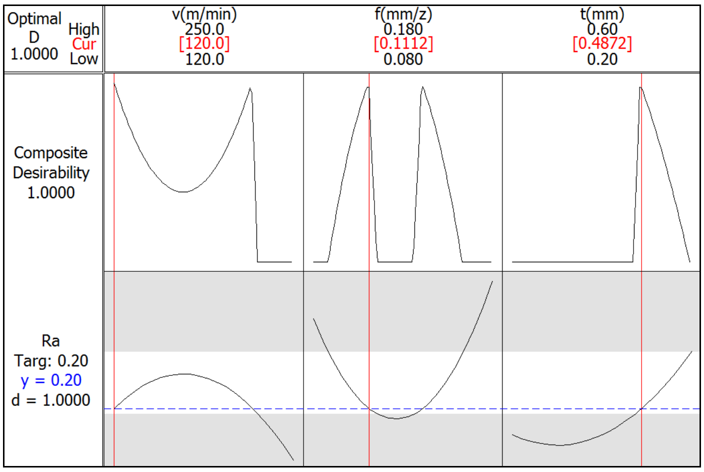

Figure 7: Optimal Graph of the Objective Function R_a.

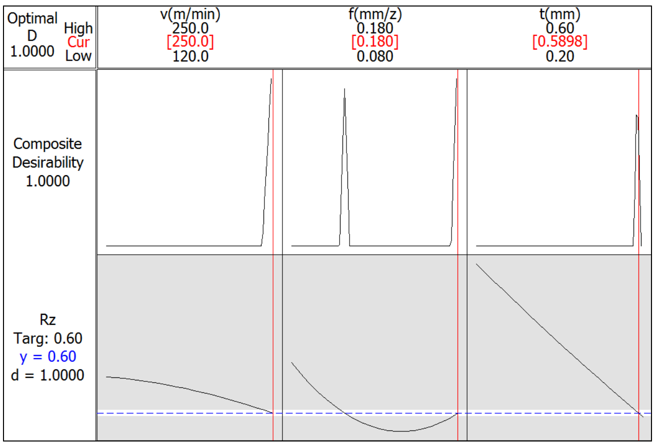

Figure 8: Optimal Graph of the Objective Function R_z.

Figure 7 and Figure 8 show that: In both cases, the desirability function has a value of d = 1, meaning that the ability to achieve surface roughness as results in those graphs can be up to 100%. However, from these two graphs, the optimal parameter set value of the cutting parameters when performing the separate optimization of each Ra and Rz parameters is quite different. This may lead to the possibility that the parameters set of the cutting parameters Ra has the smallest value but will not ensure Rz has the smallest value, and vice versa. To verify this comment, we perform the

following test: taking the optimal value of the cutting parameters when solving the optimization problem of the objective function Rz to predict the Ra value according to the formula (5). Specifically, replace the value of the cutting speed, the feed rate and the depth of cut with the corresponding values of 250 (m/min), 0.18 (mm/z) and 0.5898 (mm) into the formula (5). We determine the result Ra = 2.99 (µm), this value is much larger than the Ra value when solving the optimization problem of the objective function Ra (Figure 7). Thus, it is clear that the above statement is completely grounded. This aspect also shows that, in order to ensure the machining surface has a small roughness, it is necessary to determine the set of values of the cutting parameters to ensure that both Ra and Rz parameters are small at the same time. This is also the reason why it is necessary to simultaneously optimize the two criteria Ra and Rz in this study.

4. SIMULTANEOUS OPTIMIZATION OF SURFACE ROUGHNESS

The optimization problem of multi-objective function is written in the form:

$$\begin{cases} R_a = f(v,f,t) \rightarrow min \\ R_z = f(v,f,t) \rightarrow min \\ R_a > 0 \\ R_z > 0 \\ 120 \leq v \leq 250 \\ 0.08 < f < 0.18 \\ 0.2 < t < 0.6 \end{cases} \tag{7}$$

In the general case, for multi-objective functions, the optimal solution will correspond to the harmonic mean value of the objectives, and the expression (7) is written as follows [6]:

$$\begin{cases} f(x) = \left(\dfrac{1}{R_a} + \dfrac{1}{R_z}\right)^{-1} = \dfrac{R_a * R_z}{R_a + R_z} \rightarrow min \\ R_a > 0 \\ R_z > 0 \\ 120 \leq v \leq 250 \\ 0.08 < f < 0.18 \\ 0.2 \leq t \leq 0.6 \end{cases} \tag{8}$$

The Generalized Reduced Gradient (GRG) algorithm is used by Microsoft for optimization in Excel via the Solver tool [7]. The advantage of using Solver/ Excel to solve the optimization problem is that it doesn't require programming, and Excel is a software familiar to most people using computers [8]. Figure 9 shows the program interface when optimizing the multi-objective function using the GRG algorithm. The values of the cutting parameters as well as the Ra, Rz values when solving the optimization problem are presented in Table 4. Using the set of cutting parameters in this table, to conduct experiments on three components. Ra and Rz values of three components are also presented in Table 4.

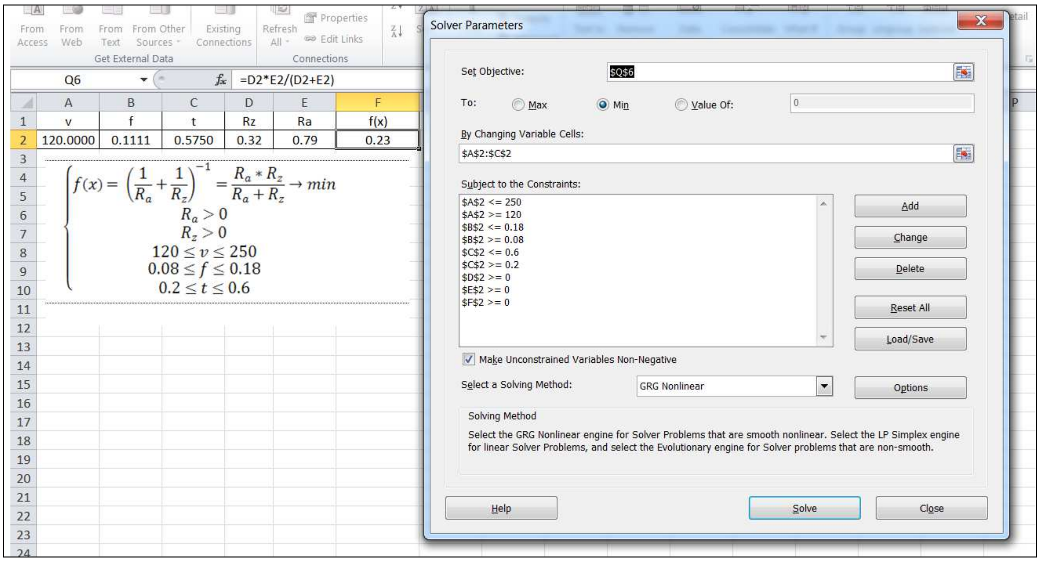

Figure 9: Excel Program Interface when Solving the Optimization Problem Using the GRG Algorithm.

Table 4: Optimal Values and Experimental Values

Cutting parameter			Optimization		Measured					
v	f	t	R_a	R_z	R_{a1}	R_{a2}	R_{a3}	R_{z1}	R_{z2}	R_{z3}
m/min	mm/z	mm								
120	0.1111	0.575	0.32	0.79	0.45	0.44	0.40	0.72	0.82	0.86

The data in Table 4 show that the optimal values of cutting speed, feed rate and depth of cut are 120 (m/min), 0.1111 (mm/z) and 0.575 (mm), respectively. When processing with this set of parameters, the average values of Ra and Rz are 0.43 µm and 0.80 µm, respectively.

5. CONCLUSIONS

The roughness of the workpiece surface is a combination of several parameters to be evaluated, of which Ra and Rz are two necessary parameters that must be considered simultaneously in each specific case. To ensure that the surface of the parts has a small roughness, make sure that both the Ra and Rz values are small. This study has identified a set of cutting speed, feed rate and depth of cut to ensure that both Ra and Rz values are small when milling 40Cr steel with a face mill.

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AUTHORS PROFILE

Dr. Nguyen Hong Son, was born in 1978, in Ha Nam province, Viet Nam. He received the B.Sc., M.Sc. and Ph.D degrees from Hanoi University of Science and Technology, Vietnam in 2001, 2005 and 2015. He is currently a lecturer and researcher of Center for Mechanical Engineering, Hanoi University of Industry (HaUI)

Main Works

- Cutting process simulation
- Cutting process optimization
- Machining modeling
- Machining prediction
- Mechanical engineering
- Elastic aerodynamics and numerical calculations
- Software in Mechanical engineering
- Design of Experiments (DOE)

Membership in Academic Societies

- Reviewer of Vietnam Journal of Science and Technology (VJST).
- Reviewer of Vietnam Mechanics Association.
- Reviewer of national journals and international journal of science

He authored/co-authored nearly 20 International Journal papers and International Conference papers.

Dr. Do Duc Trung was born in 1982, in Nam Dinh province, Viet Nam. He received the B.Sc., M.Sc. and Ph.D degrees from Thai Nguyen university of technology in 2005, 2010 and 2016. Faculty of Mechanical Engineering, Hanoi University of Industry, Vietnam. 2005 - 2017: Faculty of Mechanical Engineering, Economic and Technical colleges Thai Nguyen, Vietnam. He was leader of mechanical engineering group.

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- Reviewer of Vietnam Journal of Science and Technology (VJST).
- Reviewer of the ICERA 2018 & 2019 (International Conference on Engineering Research and Applications)
- Member of Vietnam Mechanics Association.
- Reviewer of national journals and international journal of science

He authored/co-authored nearly 40 International Journal papers and International Conference papers.